

## Cold Helium Pressurization for Liquid Oxygen / Liquid Methane Propulsion Systems: Fully-Integrated Hot-Fire Test Results

R. L. Morehead, AIAA Member  
M. J. Atwell, AIAA Member  
J.C. Melcher, AIAA Senior Member  
E.A. Hurlbert, AIAA Member

### Abstract

Hot-fire test demonstrations were successfully conducted using a cold helium pressurization system fully integrated into a liquid oxygen (LOX) / liquid methane (LCH<sub>4</sub>) propulsion system (Figure 1). Cold helium pressurant storage at near liquid nitrogen (LN<sub>2</sub>) temperatures (-275 degF and colder) and used as a heated tank pressurant provides a substantial density advantage compared to ambient temperature storage. The increased storage density reduces helium pressurant tank size and mass, creating payload increases of ~35% for small lunar-lander sized applications. This degree of mass reduction also enables pressure-fed propulsion systems for human-rated Mars ascent vehicle designs. Hot-fire test results from the highly-instrumented test bed will be used to demonstrate system performance and validate integrated models of the helium and propulsion systems. A pressurization performance metric will also be developed as a means to compare different active pressurization schemes.



Figure 1: Hot-Fire Testing of the Cold Helium Pressurization system  
integrated with vehicle test bed

Integrated hot-fire tests were conducted at NASA Johnson Space Center (JSC) in September, 2015 using the integrated propulsion test bed, Morpheus. The vehicle test bed provides an operational test platform complete with propellant tanks, feedsystems, main engine, reaction control system (RCS), and avionics for control and data acquisition. Previous ground and flight testing of the Morpheus test bed in 2013-2014 was conducted in blowdown mode (i.e., no active pressurization system). For testing in 2015, a commercially-available, cryogenic 19" diameter composite overwrap pressure vessel (COPV) was added to the vehicle test bed for helium pressurant storage (Figure 2). A ground-supplied liquid nitrogen (LN2) active cooling system was installed as a jacket surrounding the helium COPV, and aerogel-based insulation enclosed the COPV/LN2 cooling jacket. Helium was loaded into the COPV at 3600 psig and cooled in situ to -300 degF.



Figure 2: Helium COPV installed on vehicle test bed with LN2 thermal shroud and aerogel-based insulation

The cold helium was warmed from the storage temperature conditions for use as a propellant tank pressurant using a nozzle-mounted heat exchanger (HEX) integrated into the main engine. The main engine used for testing was a 2,000 lbf sea-level LOX / LCH<sub>4</sub> thruster with 5:1 throttling and an ablative chamber. The Inconel helium HEX was designed specifically for this application and installed onto the aft exit plane of the ablative chamber (Figure 3). Prior to the helium HEX design, an additively-manufactured (i.e., 3-D printed) water-cooled HEX was hot-fire tested on the 2,000 lbf thruster at NASA Stennis Space Center (SSC) (Figure 4). The SSC water-flow data provided heat-flux data across the 5:1 throttling range of the thruster, indicating ~1.7 BTU/sec/sq.in. at max throttle down to ~0.8 BTU/sec/sq.in. at min throttle.

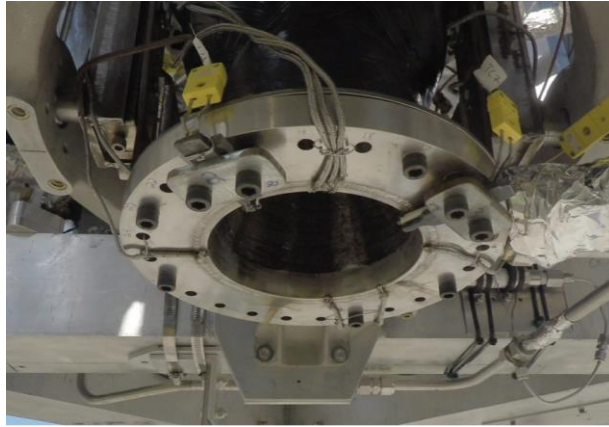


Figure 3: Inconel helium heat exchanger (HEX) Installed on 2,000 lbf Thruster Nozzle Exit.

The cold helium pressurization system used available pneumatic components from the Space Shuttle main propulsion helium system and other production launch vehicles (Figure 5). The system design incorporated regulators downstream of the main engine HEX reducing the line pressure from 3,600 psi to ~285 psig. This configuration required the HEX design to tolerate high pressure and a wide range of flow conditions but avoided the higher frictional losses and tank pressure slump associated with a regulator upstream of the HEX. Separate branches were used downstream of the HEX and inline filter to pressurize the LOX and LCH<sub>4</sub> tanks, with each branch composed of an isolation valve, regulator, relief valve, and check valve.

The vehicle test bed was augmented with additional instrumentation to measure the integrated performance of the helium pressurization system. Pressure sensors were placed at numerous locations in the helium system and between the propellant tanks to measure the repress system performance. The helium COPV was equipped with six grounded-tip Type T thermocouples to measure the axial distribution of helium temperature within the tank, and an additional five thin film thermocouples to measure the external temperature of the COPV. The main engine HEX used eight welded-on Type K thermocouples to measure the HEX hotwall and body temperatures, and exposed-tip Type K thermocouples to measure the inlet and outlet helium temperatures. Additional exposed-tip Type K thermocouples measured the helium temperature leaving the helium regulators. Each of the four propellant tanks was augmented with a rake of six exposed-tip Type T thermocouples to measure the axial distribution of the ullage gas during testing. Additionally, each propellant tank has a distribution of six external thin-film Type T surface thermocouples. Lastly, three exposed-tip Type K thermocouples were inserted into the engine nozzle hot-gas boundary layer at the exit plane of the engine-mounted HEX.



Figure 4: 2,000 lbf thruster testing at SSC using a water calorimeter heat exchanger

Test operations began with an operational dry run and two functional “wet” runs, during which cold helium loading operations were optimized and vehicle leak checks and troubleshooting were completed. Ground loading of the helium COPV was conducted in two phases. First, a low-pressure load to ~1,200 psi (with active LN2 cooling) was conducted from a 3,500 psig tube trailer, resulting in ~3.5 lbm of helium loaded in the COPV. This tank pressure was the personnel exposure limit for the COPV at cryogenic temperatures, defined by the zero-load pressure of the COPV composite overwrap (the pressure at which the composite overwrap of the COPV begins to experience tensile loading). Leak checks and trouble-shooting were conducted at this pressure as well as manual LO2 and LCH4 propellant loading operations. The second step loaded the COPV to 3,600 psig and LN2 temperatures from an array of 6,000 psig helium bottles that were remotely-controlled after personnel were cleared from the test pad area. Tank pressurization occurred rapidly but once reaching a steady state pressure transitioned to a trickle flowrate as the helium cooled and drew in more mass. Over both loading steps, ~1.5 hours was required to load the target 8.8 lb of helium. Shortly before hotfire operations, the propellant tanks were pressurized using helium from a tube trailer to ~280 psig.

Fifteen (15) successful hot-fire tests were completed during the test campaign over five hot-fire test days, covering a range of objectives. Operation of the system was conducted at varying test durations, culminating with a 60 sec duration test. Main engine throttling without chug was demonstrated down to 20% (5:1 throttling) through numerous intermediate throttle steps. Lower throttle steps down to 6% thrust were demonstrated, but chug-like pressure oscillations were recorded around 15% that subsequently cleared below the 10% throttle step (note that SSC testing also showed chug at ~15% throttle).



Figure 5: Helium system regulation and control components installed in the integrated test bed.

The main engine mounted helium HEX was a three-pass circumferential heat exchanger with a conical interior hotwall surface, increasing the nozzle area ratio from 3.1 to 3.25. The HEX worked as designed, producing helium within the design outlet temperature range without overheating the hot wall at all engine throttle levels. Helium mass flow through the HEX varied passively with engine throttle level as propellant was drawn from the propellant tanks. Engine nozzle heat flux also varied with throttle level, so the HEX was designed to balance both transients. Test data shows the reduction in helium mass flow due to throttling was outpaced by the reduction in nozzle heat flux, resulting in an overall reduction in both HEX hotwall and outlet temperatures at lower throttle levels.

Maximum hotwall temperatures of the Inconel HEX were less than 600 degF at the 20% throttle position, and less than 1,600 degF at 100% throttle. Note that some hotwall thermocouples indicated up to 1,800 degF during early testing, but those thermocouples were inadvertently protruding into the hot gas boundary layer (as seen on camera). Improving the weld bead contour of those thermocouples produced in-family temperatures. Helium HEX gas  $\Delta T$  (outlet-inlet temperature) at steady flow conditions ranged from 325 degF at full throttle to 150 degF at 20% throttle. Data shows that the heat flux measured from the helium data is slightly less than the water flow data from SSC, as expected by the higher cooling capacity of the water flow and higher overall thermal resistance of the helium HEX relative to the water calorimeter. Hot-gas boundary layer thermocouples typically reported a temperature gradient of ~1,700 to 2,250 degF between plume penetration depths of 0.05" to 0.38". Nozzle wall hot streaks indicated temperatures of 2,100 degF at 0.05" penetration. The average of these readings is similar to the wall temperature predicted by the measured heat flux.

The COPV helium inlet/exit was located at the top of the tank. The inlet did not include a diffuser, so the tank contents mixed during rapid loading. Stratified temperature layers



formed relatively quickly during both quiescent timeframes and the trickle-fill stage of helium loading. Thermocouple rakes in the helium COPV show a relatively small amount of stratification during hot-fire operation. During hot-fire usage, the COPV temperature drop was relatively consistent across all temperatures on the rake.

Thermocouple rakes in the propellant tank ullage gas show a strong amount of stratification prior to each hotfire, with only minor changes during active hotfire pressurization. External skin thermocouples show a similar response, albeit dulled by the tank wall thermal mass. The propellant tanks do not use a diffuser at the helium injection location, but perpendicular helium injection into the cylindrical upper tank boss arrested most of the injection velocity, reducing ullage mixing. Tank and ullage gas temperature data will be compared to ullage mixing CFD models and reported in the final version of this paper.

The nominal propellant tank fill level for this series of tests was ~25% liquid, resulting in large ullage volumes at the start of each test. Future testing of this integrated cold helium repress system (expected in 2016) will expand the test cases to include 50-95% full propellant tanks and longer main engine hotfire durations. Active repressurization with nearly full propellant tanks will result in increased ullage mixing, a marked decrease in pressurization efficiency, and should bound the performance envelope for the installed cold helium system.